1 Battery

This section provides hypervelocity impact test data for two types of batteries: Lithium-Ion (Li-Ion) and Nickel Hydrogen (Ni-H_2) batteries. The impact tests were directed by the NASA Johnson Space Center Hypervelocity Impact Technology (HVIT) group in Houston Texas, and were performed at the NASA White Sands Test Facility (WSTF).

1.1 Damage Mode

Li-ion batteries have been selected to replace Ni-H_2 batteries for the International Space Station (ISS) program to meet the energy storage demands while the ISS is in the Earth's shadow during its approximate 90 minute low Earth orbit. ISS battery boxes are located on the exterior of ISS and are exposed to micrometeoroid and orbital debris (MMOD) impacts. Dedicated MMOD shields on the battery boxes reduce failure risk to an acceptable level.

Hypervelocity impact testing was performed to develop and verify the MMOD shields protecting the Li-ion battery cells (consisting of aluminum honeycomb panel and additional fabric layers), as well as to understand the consequences if at some point in the operation of the ISS a MMOD particle overwhelms the shielding designed for the Li-ion battery packs and damage battery cells to cause a short circuit or a thermal runaway of the cell. Thermal runaway events have been experienced in terrestrial applications of the Li-ion battery and have the potential to propagate to neighboring cells. If thermal runaway occurs in one cell, even undamaged adjacent cells can over-heat and transition into thermal runaway conditions. Fully charged Li-ion battery cells that are representative of two possible candidates for ISS operations were impacted in hypervelocity impact tests by projectiles that easily defeat the designed shielding for the ISS external battery packs. Even though this is a low probability event, the tests were performed to evaluate if the proposed design prevented the loss of multiple cells due to propagation of thermal runaway from the impacted cell to adjacent cells.

Hypervelocity impact tests were also performed on Ni-H_2 batteries representative of ISS Ni-H_2 battery cells, which are contained within a box that is made from aluminum honeycomb sandwich panels. The Ni-H_2 battery cells were fully-charged and pressurized with hydrogen to 60 atm prior to the impact tests. The failure mode of concern is a rupture and fragmentation of the pressure shell of Ni-H_2 battery cell, and propagation to neighboring cells.

1.2 Li-Ion Impact Experiments

Hypervelocity impact conditions on Li-ion cells are summarized in Table 1.2-1. Each test article used two separate Li-ion battery cells but only one was targeted. A second cell is included to determine if failure can propagate to a nearby undamaged cell. The impact locations were typically at the terminal end of the battery cells, although some shots to the side of the Li-ion battery were also performed. Two different types of Li-ion batteries were tested with similar results. When penetrated, the impacted Li-ion battery typically increases in temperature while the cell contents are ejected and can in some cases auto-ignite. The neighboring cell will in most cases increase in temperature, but only occasionally will the temperature increase substantially resulting in failure of the undamaged cell due to thermal runaway. A sequence of images of the Li-ion battery response from one test is shown in Figure 1.2-1. This test resulted in a visible deflagration as the impacted cell contents were energetically ejected over a several second time period following cell penetration. The aluminum honeycomb panel in front of the cell was severely melted due to the expelled cell material (Figure 1.2-2a). The neighboring cell did not transition into thermal runaway. Figure 1.2-2b shows the cells after the impact test.

Table 1.2-1. Li-Ion cell impact conditions.

Test #	Projectile Diameter (mm)	Impact Obliquity (°)	Impact Speed (km/s)	Cell Damage Measurements (mm)
HITF12143	10.0	0	6.86	Primary cell-Perforated with peak temperature of 184°C Secondary cell-No ignition or thermal runaway
HITF12144	10.0	0	7.02	Primary cell-Perforated, no ignition, peak temperature 194°C Secondary cell- Thermal runaway peaking at 531°C
HITF12145	10.0	30	7.05	Primary cell-No Perforation Secondary cell-No Perforation
HITF12147	13.5	45	6.88	Primary cell-Perforated with peak temperature of 193°C Secondary cell- Thermal runaway peaking at 315°C
HITF12148	10.0	0	7.19	Primary cell-Perforated, no ignition Secondary cell-No ignition or thermal runaway

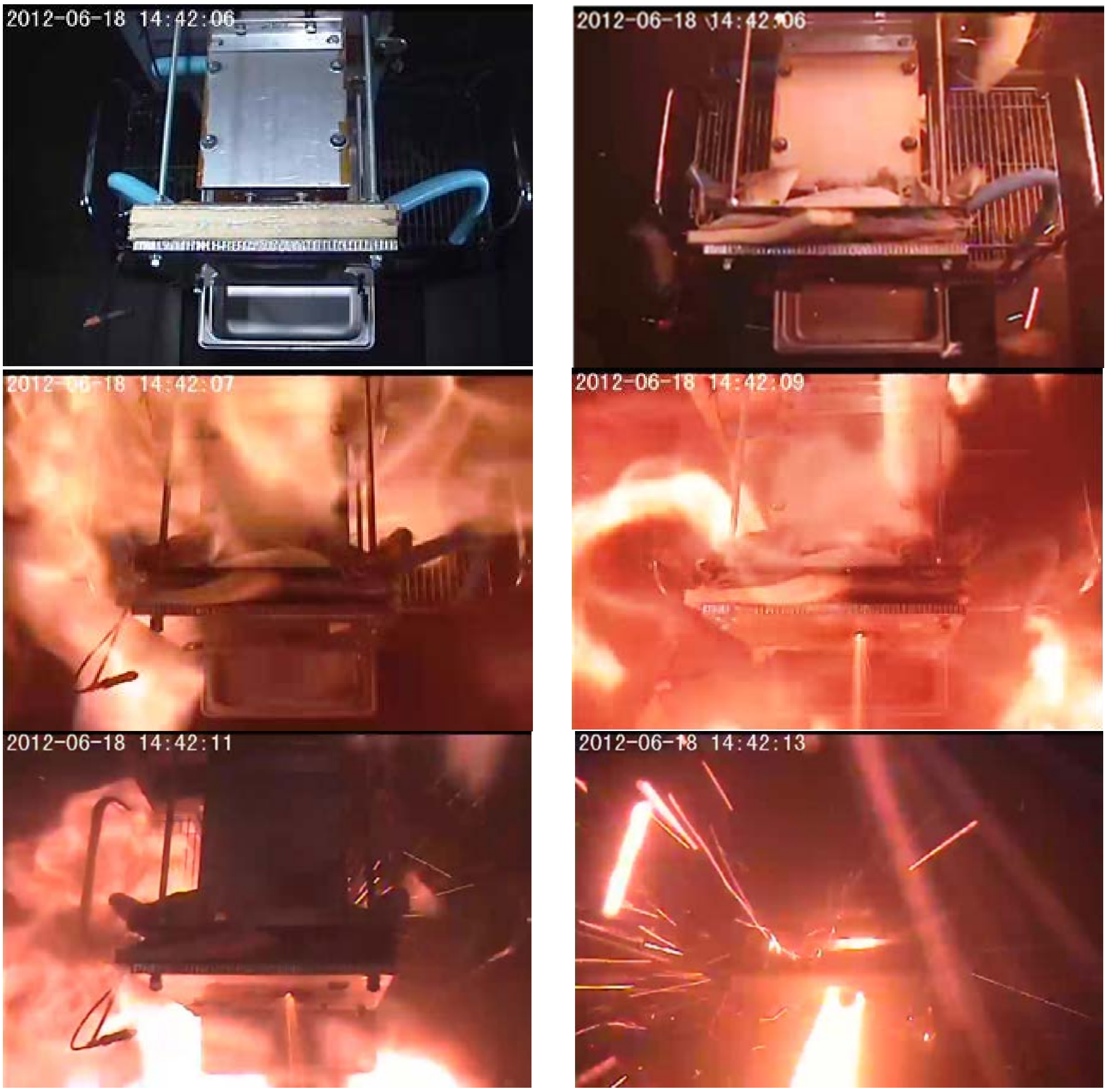

Figure 1.2-1. HITF12143 visible video frames at 1s-2s intervals after impact.

a) b)

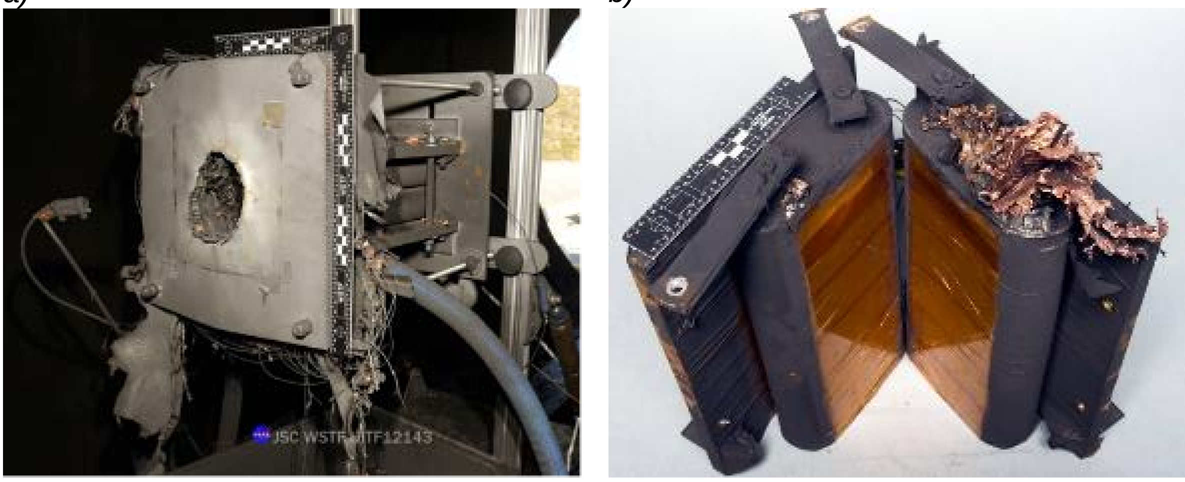

Figure 1.2-2. After test imagery of HITF12143 a) shield with 9.5cm diameter through-hole, and b) cell close-up with impacted cell on right showing molten material from cell interior that was ejected and deposited on exterior of cell.

1.3 Ni-H_2 Cell Impact Experiments

Ni-H_2 battery hypervelocity impact tests were performed on a legacy configuration of the ISS orbital replacement unit (ORU) battery assembly as shown in Figure 1.3-1. Thirty-eight cylindrical battery cells are contained in the enclosure as seen in Figure 1.3-1b. The Ni-H_2 battery cells are constructed from Inconel 718 with minimum thicknesses in the cylinder of 0.8 mm and the dome of 0.65 mm.

a) b)

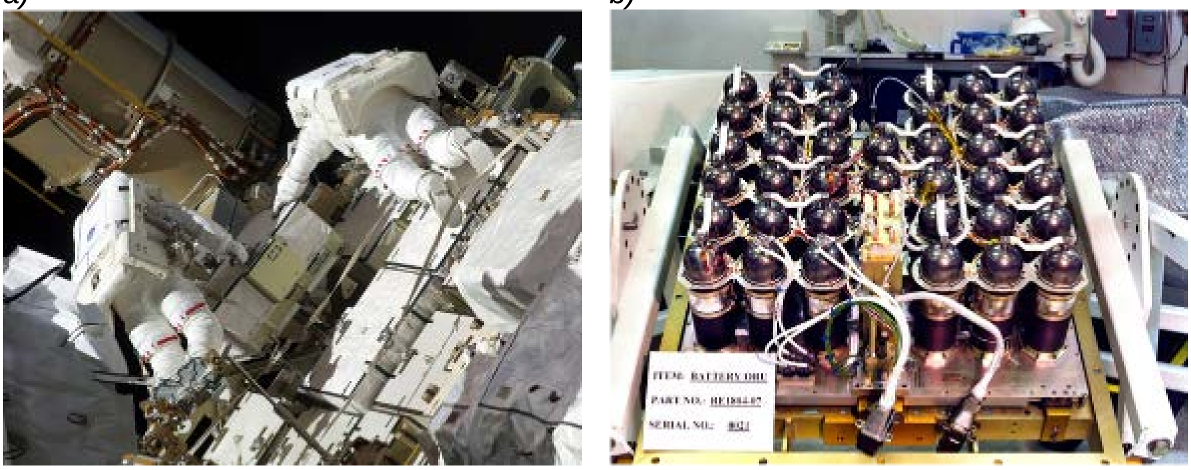

Figure 1.3-1 a) ISS Ni-H_2 battery ORU and b) ORU subassembly without enclosure.

The Ni-H_2 cell considered in this testing generates hydrogen gas in the free cell volume as a result of the chemical reactions that occur during charging. The hydrogen accumulates up to a design pressure of 6 MPa which indicates 100% state of charge (SOC) for the rated 81 ampere-hour (Ah). The cells contain an aqueous potassium hydroxide (KOH) electrolyte solution. The cells were proof tested to 10.3 MPa and have a burst pressure of 37.2 MPa. The burst factor for this cell is 6 (burst pressure/operating pressure). In the event of over-pressurization, the cells are designed to leak before burst. Impact testing was performed to determine if the vessel fragments after penetration and to assess if there are any adverse reactions with the electrode materials, thermal events or cascade failure responses.

The enclosure consists of an aluminum honeycomb panel with 0.4 mm facesheets separated by 12.7 mm thick honeycomb that is covered by a multi-layer insulation blanket (0.086 g/cm^2).

The Ni-H_2 impact conditions are summarized in Table 1.3-1. These tests impacted through the aluminum honeycomb enclosure, and were targeted to consider three basic locations on the Ni-H_2 battery: in the dome, into the terminals on the top of the domes, and into the side. Various aluminum and steel projectile diameters were used in the tests, at impact speeds of 7 km/s and impact angles of 0° and 45° to the normal of the honeycomb panel. None of the tests resulted in fragmentation of the cells. No thermal events or cascading failures resulted to neighboring cells. The largest perforations are shown in Figure 1.3-2a (test HITF13144) and Figure 1.3-2b (test HITF13165). Generally, the response to cell perforation was that the Ni-H2 cell vented and the voltage across the terminals declined until the cell could no longer maintain current over a load. In one case, the battery box cover was deformed because cell venting occurred so quickly that the box pressure increased sufficiently to deform the cover.

Table 1.3-1 Ni-H_2 impact conditions.

Test #	Impact Location	Projectile Diameter (mm)	Impact Obliquity (°)	Impact Speed (km/s)	Cell Damage Measurements (mm)
HITF13144	Dome	5.0	0	6.66	11.5 x 10.0 Perforation
HITF13145	Dome	4.0	0	6.86	1.0 x 1.5 Perforation
HITF13146	Dome	3.8	0	7.09	1.5 x 2.4 Perforation
HITF13147	Dome	3.4	0	7.09	2.4 x 3.5 Perforation
HITF13148	Dome	3.0	0	7.00	2.5 x 1.5 Perforation
HITF13149	Dome	2.8	0	7.19	No Perforation
HITF13151	Terminal	2.9	0	7.19	No Perforation
HITF13152	Terminal	3.1	0	7.12	No Perforation
HITF13153	Terminal	3.3	0	6.85	No Perforation
HITF13154	Terminal	4.2	45	7.13	1.6 x 1.2 Perforation
HITF13155	Terminal	3.0*	45	7.00	1.5 x 1.5 Perforation
HITF13158	Dome	5.0	45	7.13	2.0 x 2.0 Perforation
HITF13159	Dome	4.0	45	7.00	No Perforation
HITF13160	Dome	4.2	45	7.07	1.8 x 08 Perforation
HITF13162	Terminal	5.0	0	7.05	7.5 x 7.0 Perforation
HITF13163	Terminal	4.8	0	7.07	No Perforation
HITF13164	Terminal	5.1	0	7.04	3.0 x 1.0 Perforation
HITF13165	Terminal	3.8*	0	6.87	18.0 x 8.0 Perforation
HITF13174	Side	4.1	45	7.04	1.0 x 4.0 Perforation
HITF13175	Side	3.9	45	7.04	No Perforation

a) b)

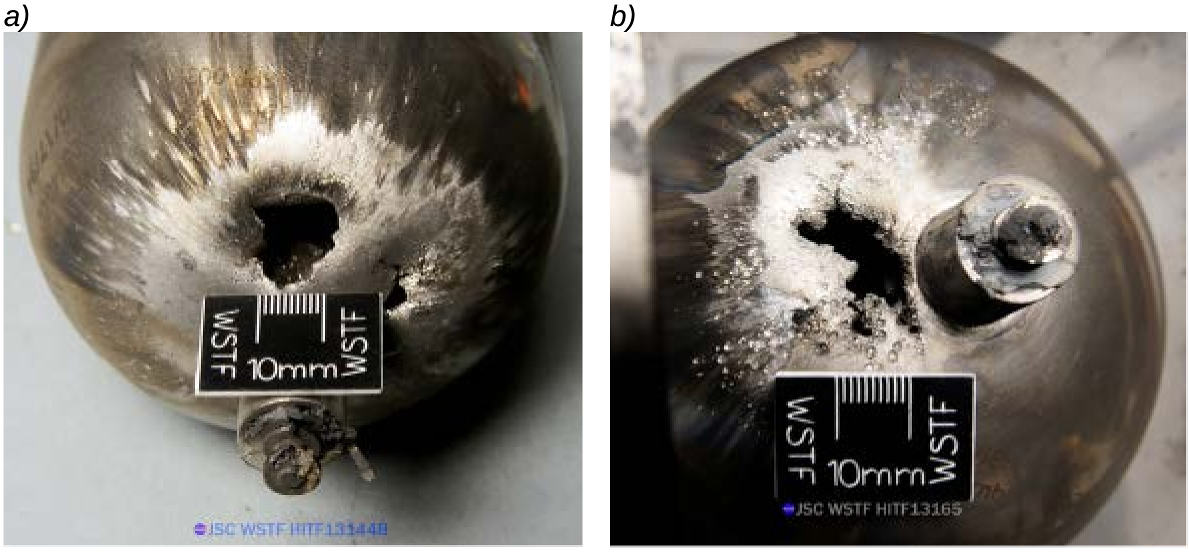

Figure 1.3-2 ISS a) HITF13144 and b) HITF13165.

1.4 Recommendations

The use of rechargeable batteries in orbital spaceflight requires consideration of the uncontrolled energy release from a cell, which is dependent on the type of cell. Impact

experiments have evaluated the failure mechanisms of the pressurized Ni-H_2 battery cell and the charged Li-Ion battery cell. For the operational design of the Ni-H_2 battery like those used on the ISS, the hydrogen gas will vent on perforation of the battery vessel; but unusual thermal events or catastrophic rupture did not occur. The ISS Ni-H_2 battery cells have a relatively high burst factor of 6. When pressurized battery cells are used in other spacecraft, attention to the burst factor of the cell should be taken into account.

Impact tests on Li-ion battery cells demonstrated an energetic release of energy when shielding is overmatched and the cell is penetrated. The impacted cell typically will overheat and will vent/eject the internal contents of the cell, including molten metal, rapidly after impact (within a few seconds). In some cases the venting material will auto-ignite, even in the vacuum environment of the test chamber. Depending on the design of the battery cell enclosure, neighboring Li-ion cells can also experience increases in temperature and can fail due to thermal runaway.

Shielding for batteries could be selected based upon the type of cell to be protected, typical failure modes and the acceptability for loss of battery cells. Supplemental shielding for Li-ion batteries should be designed to meet survivability requirements without allowing perforation of the cell wall. Shield and battery designs should be verified by test to ensure they meet protection requirements.